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무선센서 시스템 응용을 위한 선박 추진 축계용 에너지 하베스터

Energy Harvester on a Ship Propulsion Shaft for Wireless Sensor System Applications

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[요 약]

본 연구에서는, 회전하는 축계에서 무선센서 시스템 응용을 위해 에너지 하베스터(EH, energy harvester)를 제안되었다. 무선 센서 시스템(WSS)에 지속적으로 전원을 공급하기 위해 EH를 직경 20 cm의 샤프트에 설계 및 구현되었다. 로터에는 샤프트에 부착된 7개의 U자형 코어에 코일이 쌍으로 감겨 있다. 고정자는 8개의 I-코어에 부착된 8쌍의 자석으로 구성되며 외부 고정 장치에 고정되었다. EH의 발전 전력은 회전자와 고정자 사이의 공기 공극, 코일의 권수, 그리고 축의 회전속도에 따라 조사되었다. 제작된 EH는 300 rpm 및 3 mm 공기 공극에서 최대 2.87 W의 전력을 생산하였다.

[Abstract]

In this work, an energy harvester (EH) on the rotating shaft has been proposed for a wireless sensor system (WSS) applications. The EH was designed and implemented to the shaft with a diameter of 20 cm to continuously power a wireless sensor system (WSS). The rotor has coils wound in pairs on seven U-shaped cores attached to the shaft. The stator consists of eight pairs of magnets attached to eight I-cores and they are fixed to an outer fixture. The generated power of the EH was investigated as function of the air gap between the rotor and stator, the number of turn of coils, and shaft speed. The fabricated EH produced power up to 2.87 W at 300 rpm and the 3 mm air gap.

Key word : Energy harvester, Propulsion shaft, Rotor, Stator, Wireless sensor system.

색인어 : 에너지 하베스터, 추진 축계, 회전자, 고정자, 무선센서시스템

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Ⅰ. Introduction

In the era of the 4th industrial revolution, the number of connected devices and sensors in the marine industry is rapidly increasing [1]. The potential utilization of wireless sensor systems is a key feature required for increased digitization and innovation, particularly in automated vessels. Wireless sensor systems (WSSs) have played a major role in the research field as enablers of applications ranging from environmental and structural monitoring of the ship. The WSSs are nowadays becoming increasingly important due to their decisive advantages and even further achieve these under long-term deployment with minimal manual configuration and maintenance. Therefore, a reliable energy supply is of utmost importance for the WSS.

Several methods of supplying a power interface to sensors on the rotating shaft have presented significant challenges such as slip rings, roll rings, transformers, radio frequency (RF) power transfer, and alternators. Conventional slip rings usually suffer from data dropouts and noise, and require frequent cleaning and brush replacement [2]. One of the optional methods to replace the slip ring is roll rings, they provide the same functionality as slip rings, but with a rolling electrical contact, which resulted in greatly reduced wear [3]. The transformers give a non-contact solution, which was identified as an important methodology for long-term use [4]. Because RF power transfer is relatively low efficiency (10-30%) [5] and an alternator could not provide power when the rotating shaft stops [6].

The hybrid method of RF power transfer and an alternator has been used to overcome the limitations of slip rings [7]. An energy harvester (EH) using mounting coils and permanent magnets for powering wireless sensors on a rotating shaft has been applied. A permanent magnet alternator (PMA) including 36 magnets and 18 coils is used to supply 68 watts of output power to an interface device on the rotating ring [8]. Furthermore, the battery can be completely eliminated with wireless charging because of its limitations of size, capacity, and charging capabilities when the shaft rotates [9].

In this work, the EH using multiple coils and magnets is used to monitor the state of the rotating propulsive shaft. For supplying power to the WSS installed on the rotating shaft, the EH was designed and fabricated.

Ⅱ. Design and Simulation

2-1 The WSS system on the rotating shaft

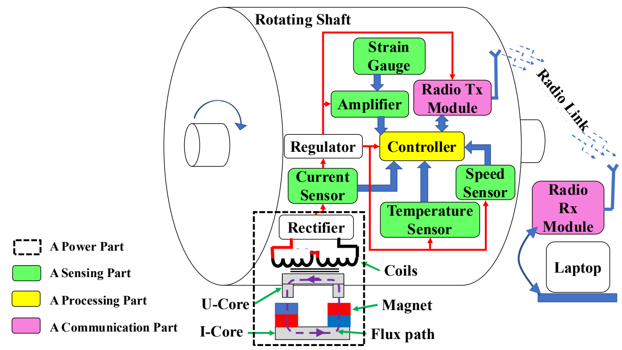


Fig. 1. Block diagram of the WSS with EH on the rotating shaft
그림 1. 회전축계에 에너지 하베스터를 포함하는 무선 센서 시스템의 블록도

Fig. 1 shows a block diagram of the WSS. There are four parts of the WSS: 1) a power part, 2) a sensing part, 3) a processing part, 4) a communication part. The power part is the EH that takes care of supplying power to the shaft for the WSS. Two coils are connected in series which cut magnetic flux generates an induced alternating current (AC) in the circuit. AC voltage was rectified using a bridge rectifier.

The end-to-end of two coils are connected to the bridge rectifier, which converts the alternating current generated in the coil pair into direct current. When working as a permanent magnet generator, the coils are rotated rapidly between the poles of square magnets. The electric current is induced depending on the position of the rotor coils with respect to the magnets. The ratio between rotor and stator poles is 7:8. This ratio always helps the rotating rotor align axes of rotor cores and stator poles at two coils of the rotor and two magnets of the stator. The sensing unit consists of four sensors (such as current, temperature, speed, and strain gauge). The current sensor measures the power consumption of the WSS. The other sensors monitor the status of the rotating shaft for condition monitoring applications, which uses various types of data (such as temperature, shaft speed, strain, torque, vibration) to judge the health of the shaft. The processing part is a central controller to sample, process data, and control the WSS. The communication part is radio Tx and Rx modules for transmitting data to the laptop. A voltage regulator is always required to supply proper and constant voltage for the WSS. For this condition monitoring application in a rotating environment, the power requirements for the WSS was estimated to have 1.5 Watt (5 VDC at 300 mA).

2-2 Design and simulation of the EH

A reliable energy source is required to use a sensor to measure a parameter of interest on a rotating shaft and communicate the measured value in a real-time application via a wireless data link. Fig. 2 shows a mechanical 3D model of the EH that converts non-electrical energy to supply power for the WSS. The rotor comprises seven U-shaped cores from the material M77 and is carried with a pair of copper coils connected in series. These U-shaped cores are fixed by an inner fixture to the shaft. Seven coil pairs are mounted on seven U-cores that are attached to the shaft with equal spacing. The stator includes magnets and I-cores. Eight pairs of magnets are attached to eight I-cores and then fixed to an outer fixture with equal spacing. The outer fixture is designed so that the distance between the rotor and stator can be varied from 3 mm to 10 mm. The I-cores are attached to two magnets at the two ends in the same face. The U-cores and I-cores are spaced evenly around the shaft circumference and inner circumference of the outer fixture, respectively.

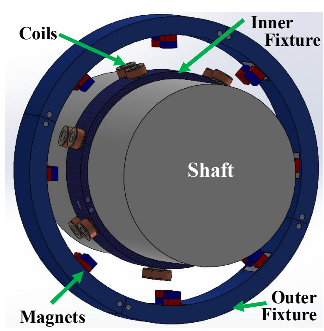
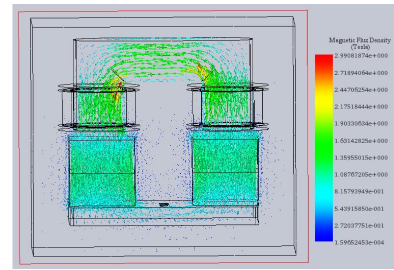
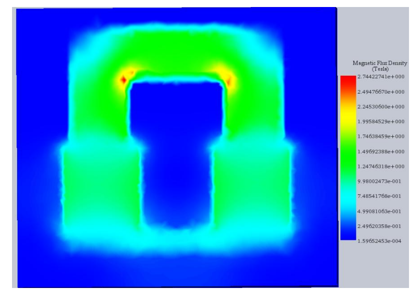


Fig. 2. A 3D model of the EH
그림 2. 에너지 하베스터의 3차원 모델

The direction of flux paths in one pole of the EH is shown in Fig. 3 (A). These flux paths match with the concept presented in Fig. 1. Main flux has to flow circumferentially along with the rotor core, so a U-core is required to help close the flux paths. Fig. 3 (B) presents the distribution of magnetic flux density on the rotor and stator pole at an aligned position. That is the time when flux density inside the coil reaches its maximum and the current in the coil is greatest. The value of magnetic flux density is about B = 1.34 T close to permanent magnetics in the stator. The circular coils have an inner radius of 0.5 cm with 1000 turns and a copper wire diameter of 0.2 mm. The polarized NdFeB N52 magnets have the size of 15 mm × 15 mm ×15 mm.



(A)



(B)

Fig. 3. Distribution of magnetic flux path in one pole of the rotor (A) and flux density at aligned position (B).
그림 3. 회전자 극에서 자속 경로 분포 (A) 그리고 정렬된 위치에서 자속 밀도 (B).

Table 1. Key parameters in design of the EH.
표 1. 에너지 하베스터 설계에서 핵심 파라미터

Parameters	Values
Shaft radius (mm)	100
Remnant Flux density Br (T)	1.43
Air gap (mm)	3 – 10
Number of rotor poles	7
Number of stator poles	8
Rotor poles	U-core
Stator poles	I-core
Size of rotor poles (mm)	41/20/11
Size of stator poles (mm)	43/4/28
Permanent magnet	NdFeB N52
Magnet size (mm)	15/15/15
Copper wire diameter (mm)	0.2
Number of turns	1000

The key parameters of the EH is summarized in Table 1. The number of poles of the rotor and stator are 7 and 8, respectively. The air gap was set at 3 - 10 mm for the fabrication process and performance.

Ⅲ. Experimental Setup and Measurement Results

3-1 Experiment Setup

Fig. 4 shows an overview of the assembled EH and WSS on a small-scale test shaft which is connected to the motor to simulate a rotating speed. The coil and magnetic core configuration were built and tested. The average resistance and inductance of the coil pairs connected in series inside the rotor core were 145 Ω and 102 mH, respectively. The I and U cores were used to enhance the magnetic coupling. A diameter and circumference of the shaft are 20.0 and 62.8 cm, respectively.

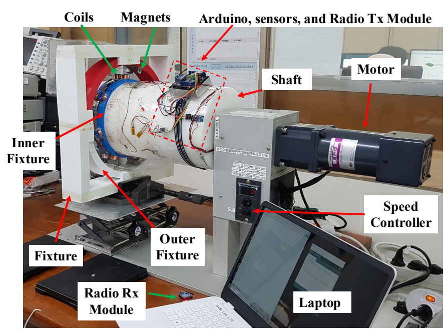
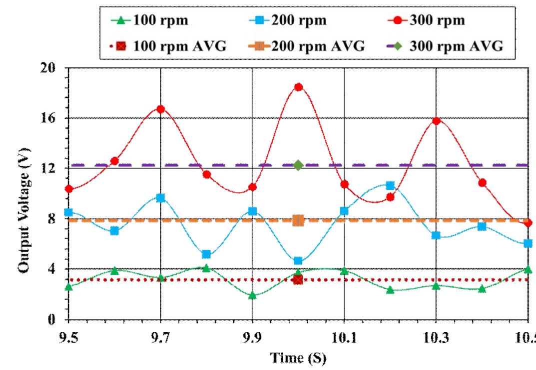


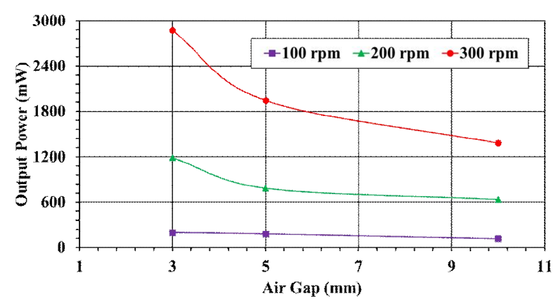
Fig. 4. Experiment setup.
그림. 4. 실험 장치

3-2 Measurement results

Appropriate load impedance matching between the harvester and the resistance load was determined to maximize the usage of the harvested energy. For the matched resistance, the EH was measured across the load resistances of 50 Ω. Fig. 5 (A) provides the output voltage of the EH with the change of shaft speed at a 3 mm air gap and 1000 coil turns. These output voltage characteristics fluctuated depending positions of the rotor and stator poles during the rotation of the shaft. The average output voltages at three experimental speeds of 100, 200, and 300 rpm are 3.18 V, 7.86 V, and 12.28 V, respectively. As expected, the output power increases with shaft speed. Before rectifiers, measured frequencies at speed levels 100, 200, 300 rpm are 5.83, 11.67, 17.5 Hz, respectively. Fig. 5 (B) and (C) present the output voltage and power as the function of the air gap between the rotor and stator at different speeds. As the speed increases, the amplitude of output voltage and power signals also increase. It could be seen that the output power could produce 2.87 W at the shaft speed of 300 rpm and 3 mm air gap. Fig 5 (B) exhibits the DC output power versus air gap at speeds from 100 to 300 rpm. As the air gap increases, its corresponding power decreases. This power is sufficient to drive WSS. The data generated from the sensors in the WSS were successfully transferred to the PC through the radio module, and it was proved that the state of the propulsion shaft can be observed.



(A)



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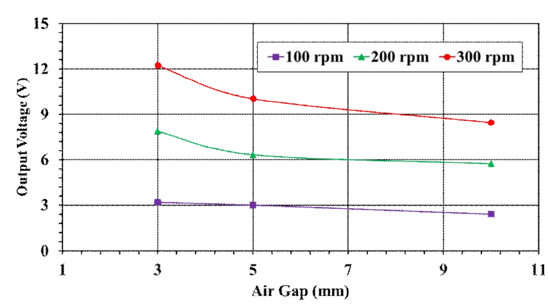
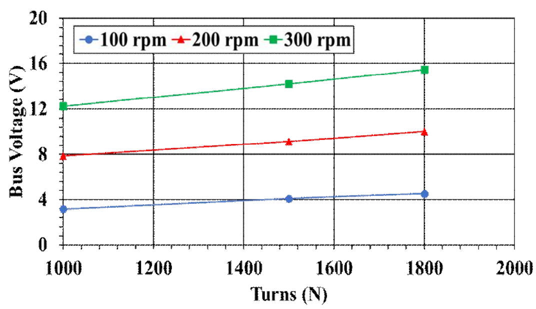


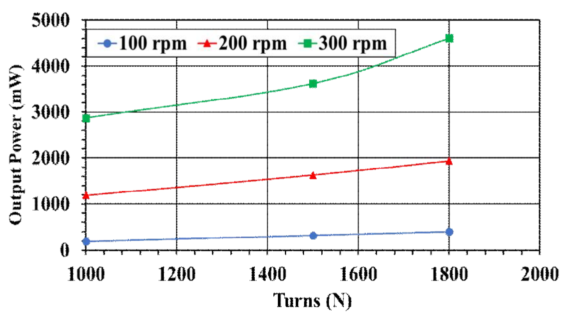
(C)

Fig. 5. Measurement results; output voltage as the function of the rotation speed of the shaft at 3 mm air gap (A), output voltage (B) and output power (C) of the EH as the function of the air gap.
그림. 5. 측정결과; 공기간극 3mm에서 축의 회전속도에 따른 출력 전압 (A), 공기 간극의 변화에 따른 출력전압 (B)과 출력 전력(C).

The EH output power is proportional to the number of the coil turns, and voltage output increased with increasing coil turns as shown in Fig. 6 (A) and (B). With the 1800 turns of each coil, the EH produces a maximum power of 4.6 W at the 3 mm air gap and shaft speed of 300 rpm.



(A)



(B)

Fig. 6. Measurement results, output voltage (A) and output power (B) of the EH as the function of the turns of the coils.
그림. 6. 측정결과; 코일의 권선 수에 따른 출력전압(A)과 출력전력(B).

Ⅳ. Conclusion

In this work, the EH using multiple coils and permanent magnets for powering to WSS on rotating shaft has been presented. The EH was designed and implemented on the shaft with the diameter of 20 cm to continuously power the WSS. The rotor has coils wound in pairs on seven U-shaped cores attached to the shaft. The stator consists of eight pairs of magnets attached to eight I-cores and they are fixed to an outer fixture. The fabricated EH was validated using the small-scale test shaft. The test shaft was driven by an electric motor with rotation speed control. The generated power of the EH was investigated as function of the air gap between the rotor and stator, the number of turn of coils, and shaft speed. The fabricated EH can produce up to 4.6 W of power at 300 rpm with 1,800 coil turns and a 3mm air gap.

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